

Subluminous O Stars – Origin and Evolutionary Links

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Abstract. Hot subluminous stars can be roughly divided into B- and O-types. Unlike the latter many sdBs are found in close binaries, indicating that binary evolution plays a vital role. Recent NLTE spectral analyses revealed that an evolutionary link between sdB stars and sdO stars is plausible only for the *helium-deficient* sdO stars, i.e. they are the likely successors to sdB stars. The atmospheric properties of *helium-enriched* sdO stars can be explained by the late hot flasher as well as by the white-dwarf merger scenarios, although both models do not match the observed properties of *helium-enriched* sdO stars in detail. The white dwarf merger scenario is favoured because it naturally explains the scarcity of close binaries amongst *helium-enriched* sdO stars. A hyper-velocity sdO star moving so fast that it is unbound to the Galaxy has probably been ejected by the super-massive black hole in the Galactic centre.

1. Hot Subluminous Stars

Hot subluminous stars are an important population of faint blue stars at high Galactic latitudes closely related to the horizontal branch. A proper spectral classification of hot subluminous stars is rendered difficult by the diversity of the helium line spectra. They can be grouped roughly into the cooler sdB stars, whose spectra typically display no or only weak helium lines, and the hotter sdO stars, which have a higher helium abundance on average and can even be dominated by helium. The former have recently been studied extensively because they are common enough to account for the UV excess observed in early-type galaxies. Pulsating sdB stars are important tools for asteroseismology (Charpinet et al. 2004), and sdB stars in close binaries may qualify as supernova Ia progenitors (Maxted et al. 2000; Geier et al. 2007).

Subluminous B stars have been identified as extreme horizontal branch (EHB) stars (Heber 1986); i.e., they are core helium-burning stars with hydrogen envelopes that are too thin to sustain hydrogen burning (unlike normal HB stars). Therefore they evolve directly to the white-dwarf cooling sequence by avoiding the asymptotic giant branch (AGB). While the sdB stars spectroscopically form a homogeneous class, a large variety of spectra is observed among sdO stars (Heber 1992; Heber et al. 2006). Most subluminous B stars are helium poor, whereas only a relatively small fraction of sdO stars are.

Ever since the pioneering work by Greenstein & Sargent (1974), the helium-rich sdO stars were believed to be linked to the evolution of the hydrogen-rich subluminous B stars. Any evolutionary link between subluminous B and O stars, however, is difficult to explain since the physical processes driving a

transformation of a hydrogen-rich star into a helium-rich one remain obscure. The convective transformation has been explored by Wesemael et al. (1982), as well as by Groth et al. (1985). While the former found helium convection even at subsolar helium abundances, which mixes helium from deeper layers into the photosphere, the latter concluded that a helium-driven convection zone develops only in helium-rich atmospheres. If the latter is true, convective transformation would not work.

The fraction of sdB stars in short period binaries (periods less than ten days) is high. Maxted et al. (2001) found 2/3 of their sdB sample were such binaries, whereas a somewhat lower fraction of 40% was found recently for the sample drawn from ESO Supernova Ia Progenitor Survey (SPY, Napiwotzki et al. 2001). Quite to the opposite, radial velocity variable stars are rare amongst the *helium-enriched* sdOs, for which Napiwotzki et al. (2004) find that a fraction of radial velocity variables to be 4% at most. Obviously, binary evolution plays an important role in the formation of sdB stars and possibly also in that of the sdO stars.

While atmospheric parameters have been determined for several hundred sdB stars (e.g. Saffer et al. 1994; Maxted et al. 2001; Edelmann et al. 2003; Lisker et al. 2005), only very few sdO stars have been analysed so far. Most of the apparently brightest sdO stars turned out to be post-AGB stars (e.g. Rauch et al. 1991; Heber et al. 1988) and shall not be discussed here. LTE model atmospheres are sufficient to analyse the B-type subdwarfs (Napiwotzki 1997), whereas NLTE is mandatory for the sdO stars rendering the analysis more difficult. Early NLTE analyses of low resolution spectra gave inconsistent results (Dreizler et al. 1990; Thejll et al. 1994). The SPY survey has provided high resolution spectra of 46 sdO stars and a new grid of model atmospheres has become available (Stroeer et al. 2007). Hirsch et al. (2008) have recently used the same grid to analyse sdO spectra from the Sloan Digital Sky Survey (SDSS). Hence, atmospheric parameters for about 130 sdO stars are now at hand, a sufficiently large number to test rivalling evolutionary scenarios. We describe the NLTE spectral analyses in the next section and compare the results from the SPY survey to evolutionary models in section 3. In section 4 we add the results from the SDSS survey. Before concluding we present the discovery of a so-called hyper-velocity sdO star in section 5.

2. NLTE Spectral Analysis of the SPY Sample

The SPY project has obtained high resolution spectra with the UVES spectrograph at the ESO-VLT for over 1000 white-dwarf candidates to test possible scenarios for type Ia supernovae by searching for double degenerate white-dwarf binary systems close to the Chandrasekhar mass limit. Many of the target stars of SPY came from the Hamburg ESO survey. SPY also observed 137 hot subluminal stars that entered the target sample because they were previously classified as white dwarfs. Seventy-six of these stars are now classified as sdB/sdOB, and 58 as O-type subdwarfs.

Stroeer et al. (2007) determined atmospheric parameters (T_{eff} , $\log g$ and $\log y$) of 46 sdO stars from SPY by fitting synthetic model spectra to the observed ones, using a χ^2 -minimisation procedure (Napiwotzki 1999) to derive

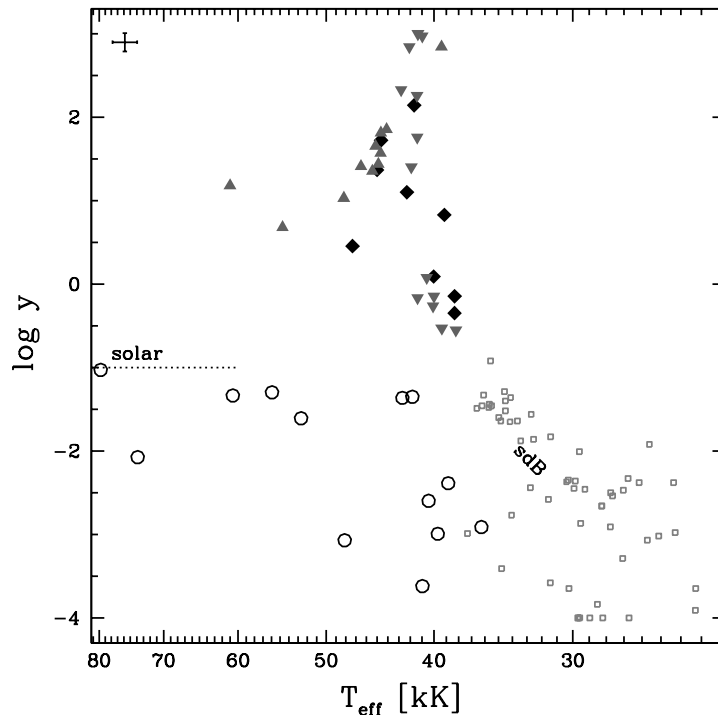


Figure 1. He/H ratio y versus T_{eff} for sdO and comparison to the sdB stars (open squares) from the SPY project. Open circles: No C and N lines; filled triangle: either N (upside down triangle) or C lines; filled diamonds: both C and N lines visible. Measurement uncertainties are given in the upper left corner (from Stroeer et al. 2007).

all three parameters simultaneously. The synthetic non-LTE models were constructed using the TMAP code (Werner & Dreizler 1999) with a new temperature correction technique (Dreizler 2003) and include partially line blanketing. It includes H and He atoms only. The model grid ranges in temperature from 30 000 K to 100 000 K and from 4.8 dex to 6.4 dex for $\log g$ with $\log y = -4 \dots +3$. No extrapolation beyond the model grid was allowed. For further details see Stroeer et al. (2007).

The results of the analysis are displayed in Figs. 1 and 2. Most strikingly a clear correlation between helium abundance and CN class becomes apparent. None of the sdO stars with subsolar helium content shows carbon and/or nitrogen lines. The opposite is true for sdO stars with supersolar helium content – all of them show carbon and/or nitrogen lines.

This suggests that the sdO stars should be grouped into two classes according to helium content. Those with supersolar helium abundances will be referred to as *helium-enriched* sdO stars, while those with subsolar helium abundances will be termed *helium-deficient* sdO stars.

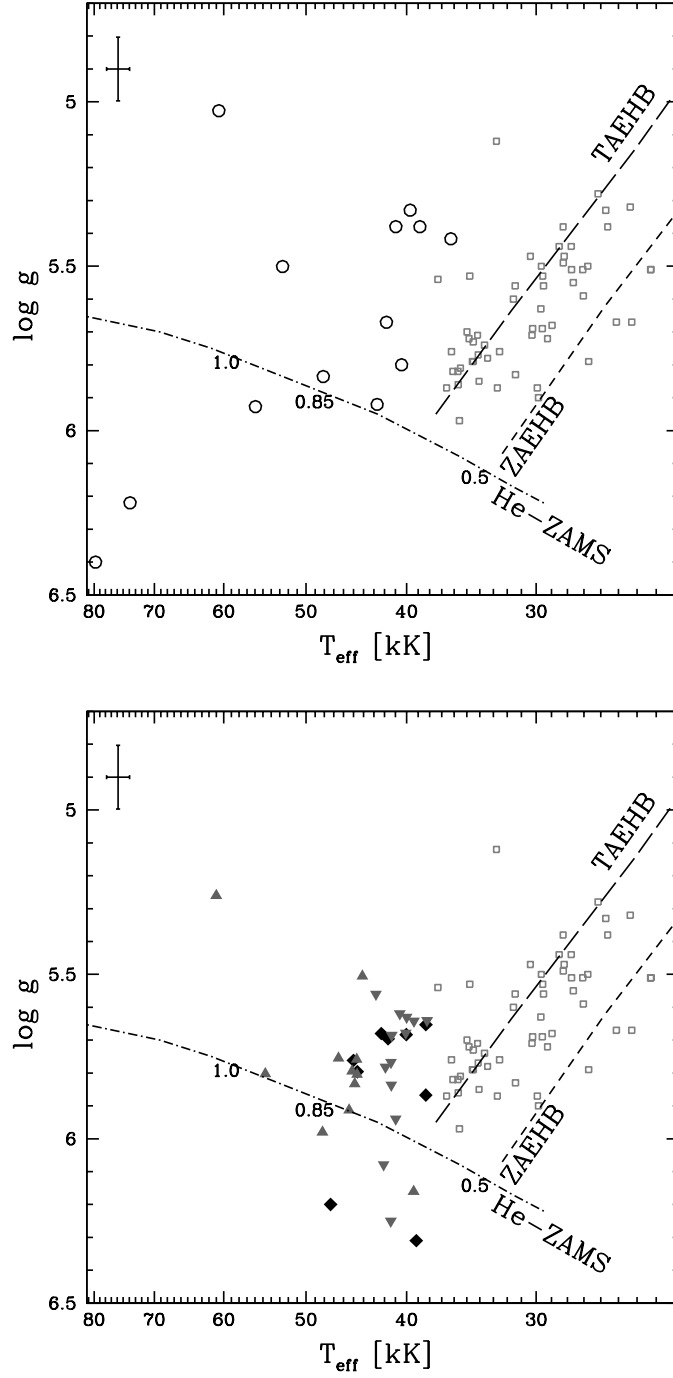


Figure 2. Top panel: *Helium-deficient* sdO stars from the SPY project: Distribution of T_{eff} and $\log g$. The EHB band and the helium zero-age main sequence are also indicated. Notation as in Fig. 1. Bottom panel: Same, but for *helium-enriched* sdO stars (from Strooeer et al. 2007).

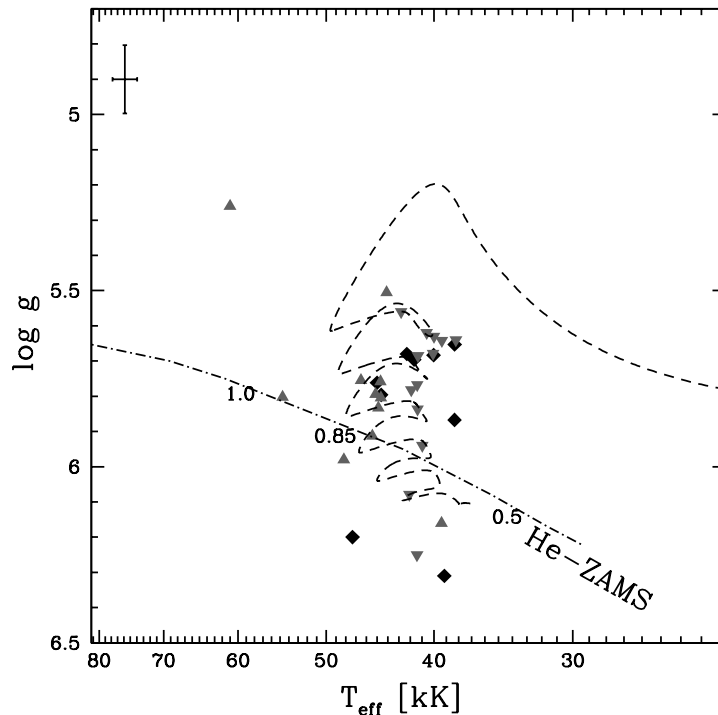


Figure 3. *Helium-enriched sdO stars*: Comparison with an evolutionary track for an EHB star formed by a delayed helium flash in the $T_{\text{eff}}\text{-log } g$ plane. The track settles onto the helium main sequence (labelled by stellar mass in solar units). Symbols as in Fig. 1 (from Stroeer et al. 2007).

While the *helium-deficient* sdO stars are scattered in a wide $T_{\text{eff}}\text{-log } g$ -range, most *helium-enriched* sdOs populate a relatively narrow region (T_{eff} from ~ 40 to ~ 46 kK and $\text{log } g$ from ~ 5.5 to ~ 5.9).

3. Evolutionary Scenarios: Late Hot Flashers, Common Envelope Ejection and White Dwarf Mergers

3.1. Late Hot Flashers

Non-standard evolutionary models were introduced to explain the formation of sdO stars (e.g. Sweigart 1997; Brown et al. 2001; Moehler et al. 2004). In particular, the *late hot flasher scenario* predicts that the core helium flash may occur when the star has already left the red giant branch (RGB) and is approaching the white-dwarf cooling sequence (delayed He core flash). During the flash, He and C may be dredged-up to the surface. Hydrogen is mixed into deeper layers and burnt. The remnant is found to lie close to the helium main sequence, i.e. at the very end of the theoretical extreme horizontal branch. In Fig. 3 the observed distribution of all sdB and sdO stars from SPY in the $T_{\text{eff}}\text{-log } g$ -diagram is compared to an evolutionary track settling to the EHB (Sweigart 1997).

The final composition of the envelope is helium-dominated, and enriched with carbon (or nitrogen if the hydrogen burning during the helium flash phase burns ^{12}C into ^{14}N ; Sweigart 1997). Indeed, most of our observed *helium-enriched* sdO stars lie near the model track, suggesting that this scenario may be viable. However, the evolutionary time scales (1.95×10^6 yrs for the evolution shown in Fig. 3) are much shorter than for the helium-burning phase (Sweigart 1997). Accordingly the stars should accumulate near the end of the track, i.e. near the helium main sequence, which is not the case for our program stars.

Although the late hot-flasher scenario can explain the helium enrichment and the line strengths of C and/or N lines as due to dredge up, it fails to reproduce the distribution of the stars in the $T_{\text{eff}}\text{-log } g$ -diagram in detail.

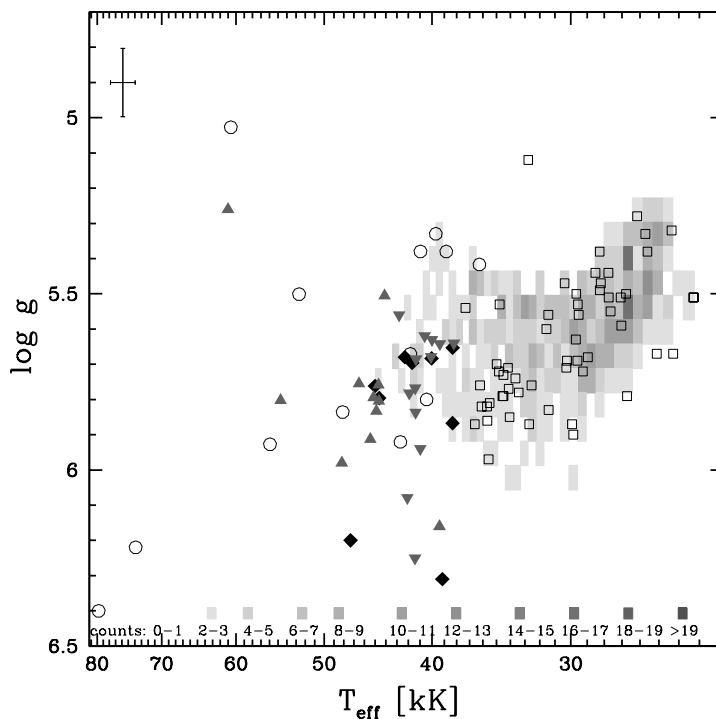


Figure 4. Comparison of the atmospheric parameters of hot subdwarfs from SPY to simulation set No. 10 of (Han et al. 2003). Shaded $T_{\text{eff}}\text{-log } g$ boxes: theoretical predictions, where a higher subdwarf density per box corresponds to darker shading (grey scale shown below). Notation same as in Fig. 2 (from Stroeger et al. 2007).

3.2. White Dwarf Mergers

Evidence has accumulated that close binary evolution is important to understand the origin of the hot subdwarf stars. A recent binary population synthesis study (Han et al. 2003) identified three channels for forming sdB stars: (i) one or two phases of common envelope evolution, (ii) stable Roche-lobe overflow, and (iii) the merger of two helium-core white-dwarfs. The latter could explain

the population of single stars. Short period binary WDs will lose orbital energy through gravitational waves. With shrinking separation, the less massive object will eventually be disrupted and accreted onto its companion, leading to helium ignition. Saio & Jeffery (2000) argue, that this merger product will result in a helium burning subdwarf showing an atmosphere enriched in CNO-processed matter. This scenario therefore can explain these extremely *helium-enriched* sdOs showing strong nitrogen lines in their atmospheres. However, Gourgouliatos & Jeffery (2006) find that, under the assumption of total angular momentum conservation, He+He WD mergers do rotate faster than breakup velocity. A mechanism that enables the star to get rid of its angular momentum still has to be found.

In Fig. 4 the observed distribution of all sdB and sdO stars from SPY in the $T_{\text{eff}}\text{-log } g$ -diagram is compared to the simulation set No. 10 of Han et al. (2003), which is characterised by a low efficiency ($\alpha_{\text{CE}} = \alpha_{\text{th}} = 0.5$), low metallicity ($Z = 0.004$), and a constant mass ratio of the progenitor binaries. This set was chosen because it came closest to the SPY-sdB distribution (Lisker et al. 2005). The simulation set is represented by two-dimensional bins in Fig. 4. The grey shading of the rectangular areas corresponds to the respective number of simulated stars they contain. Higher number densities of simulated subdwarfs correspond to darker grey shading.

From the direct comparison of the $T_{\text{eff}}\text{-log } g$ -values to the Han et al. (2003) simulations, two effects become apparent. First, sdO stars significantly exceed even the hottest temperatures predicted. Second, by restricting our analysis to stars that come close to the Han et al. (2003) predictions, i.e. those that are apparently connected with the sdB sample, a disagreement of the observational data with the simulation set becomes obvious: the relative amount of hot (sdO) and cool (sdB) stars differs significantly. The binary population synthesis models have a large number of parameters which have to be constrained by additional observations (see Sect. 4.). Moreover further refinement of the binary population synthesis models is required as well as an extension of parameter studies.

The hottest stars in the simulation set are mostly formed from white dwarf mergers. Close binaries are much rarer amongst *helium-enriched* sdO stars than amongst the sdB stars in the SPY sample (by a factor of ten). Therefore it is tempting to identify the *helium-enriched* as formed by mergers of helium white dwarfs.

4. Subluminous O stars from the Sloan Digital Sky Survey

Hirsch et al. (2008) searched the database of the 5th data release of SDSS, and selected all point sources within the colour box $(u - g) < 0.4$ and $(g - r) < 0.1$. They classified more than 8000 spectra by visual inspection, mostly white dwarfs, about 500 sdB stars and 112 sdO stars. After removing too noisy spectra and those with spectral features indicative of a cool companion, a spectral analysis of the remaining 87 sdO stars was performed using the same analysis technique and NLTE model atmosphere grid as described above. The distribution of SDSS stars in the $T_{\text{eff}}\text{-log } g$ -plane (see Fig. 5) resembles that of the sdOs from SPY quite well.

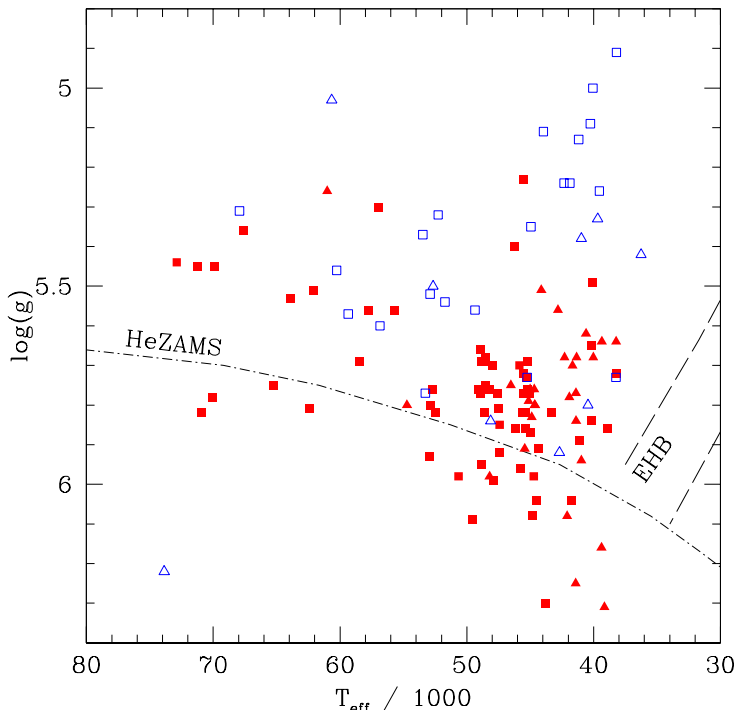


Figure 5. T_{eff} - $\log g$ -diagram: Filled symbols: *helium-enriched* sdO; open symbols: *helium-deficient* sdO. Squares: SDSS, triangles: SPY (from Hirsch et al. 2008).

The ratio of *helium-enriched* stars to *helium-deficient* ones appears to be slightly higher in SDSS than in SPY (68:18 vs 33:13). In addition, the SDSS sample contains more very hot stars ($T_{\text{eff}} > 60\,000$) than the SPY sample. Both findings are probably due to selection effects, e.g. the limiting magnitude of the surveys, which is considerably fainter for SDSS than for SPY.

In summary, the increased sample consisting of the SPY and the SDSS sample corroborates the conclusions drawn from the smaller SPY sample.

Stroeer et al. (2007) pointed out that the SPY sample contains a few stars lying below the helium main sequence, all but one are *helium-enriched*. The number was too small to draw firm conclusion. As can be seen from Fig. 5 there are also such stars in the SDSS sample confirming the significance of the discovery (unless there is a systematic error in the gravity determination of all of them). The origin of stars below the helium main sequence is difficult to explain as such stars cannot sustain stable helium burning in their cores.

5. Discovery of an Unbound Hyper-Velocity SdO star

Amongst the sdO stars drawn from the SDSS data base, Hirsch et al. (2005) discovered a so-called hyper-velocity star, US 708, in the Milky Way halo, with a heliocentric radial velocity of $+708 \pm 15 \text{ km s}^{-1}$.

A quantitative NLTE model atmosphere analysis of optical spectra obtained with the KECK I telescope shows that US 708 is a normal *helium-enriched* sdO with $T_{\text{eff}}=44\,500$ K, $\log g = 5.25$. Adopting the canonical mass of half a solar mass from evolution theory the corresponding distance is 19 kpc. Its Galactic rest frame velocity is at least 757 km s^{-1} , much higher than the local Galactic escape velocity (about 430 km s^{-1}) indicating that the star is unbound to the Galaxy. It has been suggested by Hills (1988) that such hyper-velocity stars can be formed by the tidal disruption of a binary through interaction with the super-massive black hole at the Galactic centre (GC). Numerical kinematical experiments are carried out to reconstruct the path of US 708 from the GC. US 703 needs about 36 Myrs to travel from the GC to its present position, which is shorter than its evolutionary lifetime. Hence it is plausible that the star might have originated from the GC, which can be tested by measuring accurate proper motions. A HVS survey has increased the number of known HVS to ten (Brown et al. 2007). However, US 708 remains the only bona-fide old, low mass HVS star, while all other are probably young massive stars.

6. Summary and Conclusion

According to recent quantitative spectral analyses the sdO stars should be grouped into two classes according to helium content because of a pronounced dichotomy of the carbon/nitrogen spectra. At supersolar helium abundances (*helium-enriched*) all sdO stars display C and/or N lines, while none are observed at subsolar helium abundances (*helium-deficient* sdOs). A direct evolutionary linkage of the hot sdO stars to the somewhat cooler sdB stars is plausible only for the *helium-deficient* sdO stars, i.e. the latter are the likely successors to sdB stars.

Most of the *helium-enriched* sdO stars cluster in a narrow region of the $T_{\text{eff}}\text{-}\log g$ -diagram at temperatures between 40kK and 50kK. While diffusion is probably causing helium deficiency, it is unlikely to account for the helium enrichment. Non-standard evolutionary scenarios had therefore to be invoked. The predictions from both the late hot-flasher scenario and the helium white-dwarf merger scenario are roughly consistent with the observed distribution of *helium-enriched* sdO stars but do not match them in detail. The occurrence of both a delayed helium core flash and the merger of two helium white dwarfs may explain the helium enrichment. In these cases carbon and/or nitrogen can be dredged up to the stellar surface, which would explain the strength of the C and/or N lines in *helium-enriched* sdO stars. The lack of close binaries amongst the latter is consistent with a white dwarf merger origin.

Some high gravity *helium-enriched* sdO stars lie below the helium main sequence, which is at variance with any core helium burning model. Whether the so-called He-sdB stars (Ahmad & Jeffery 2003) form a class of their own or are just the low temperature tail of the *helium-enriched* sdO stars remains to be studied. Detailed spectral analyses of high resolution spectra are urgently needed to determine C and N abundances and to derive projected rotational velocities. Both will yield tight constraints to test evolutionary scenarios.

The nature of the enigmatic double sdO star PG 1544+488 (Ahmad et al. 2004) needs to be explored further. Ahmad et al. (2004) argue that the mass of

the secondary is unusually low, i.e. too low to sustain core-helium burning. A similar sdO binary has been discovered by Lisker et al. (2004) but has not been followed up yet.

The discovery of a hyper-velocity sdO star (US 708) travelling so fast that it is unbound to the Galaxy came much to a surprise and the star remained the only low mass, evolved object of its class up to now. It is generally believed that such stars originate from the Galactic centre, because only super-massive black holes seem to be capable of accelerating stars to velocities larger than the Galactic escape velocity. Because US 708 probably is a very old star it might have been ejected from a globular cluster rather than from the GC if a black hole of intermediate mass (a few thousand solar masses) resides in the cluster (see Heber 2008).

Almost ten years after the discovery of the first multi-periodic pulsating sdB star (Kilkenny et al. 1997), the first sdO star was found to pulsate (Woudt et al. 2006). This opens up a new window to study sdO stars using asteroseismological models. For subluminescent B stars this has already resulted in the measurements of masses of the stars and their envelopes in more than a handful of cases (Fontaine et al. 2008). This technique may be very promising for sdO stars as well although appropriate models are still at their infancy.

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